



## KNOCKING DETECTION APPARATUS AND DETECTION METHOD

### BACKGROUND OF THE INVENTION

#### Field of the Invention

The present invention relates to a knocking detection apparatus and detection method that detect, with high precision, the presence of knocking and the ~~occurrence~~ timing thereof from changes in ion currents that are detected using spark plugs at the time of combustion of an internal combustion engine.

#### Description of the Related Art

It is known that ions are generated when fuel is combusted inside the cylinders of an internal combustion engine and that these ions can be measured as ion currents by disposing probes that apply a high voltage inside of the cylinders. Because knocking vibration components are superposed on the ion currents when knocking occurs in an internal combustion engine, the occurrence of knocking can be detected by detecting these vibration components.

However, ~~in a case where~~ spark noise ~~including~~ includes many frequency components ~~is~~ superposed on the ion currents, ~~this ends~~ end up being detected as vibration components of ~~the knocking,~~ and ~~is~~ are mistakenly determined to be knocking even if knocking is not actually occurring.

The following technologies have been disclosed as

technologies to avoid this drawback. First, the technology disclosed in Japanese Patent No. 3184451 (pp. 2-3, Figs. 1 and 2) ~~is disposed with~~ (Japanese Published Patent Application 9-228941) includes a bandpass filter that filters only the knocking frequency components superposed on the ion currents when knocking has occurred and a noise-~~use~~ bandpass filter that allows frequency components different from the knocking frequency components to pass. For example, by blocking ~~off-switching means when noise~~ resulting from the operation of an injector ~~is~~, when detected through the noise-~~use~~ bandpass filter, using a switch, a knocking signal is not inputted to a determination circuit.

In the technology disclosed in JP-A-11-2175 (pp. 3-4, Figs. 1 and 3), signals based on the ion currents ~~are~~ allowed to pass through a high-pass filter, ~~thereafter and~~ knocking signals ~~are allowed to pass~~ through a filter allowing a specific frequency band to pass, ~~only~~. Only the noise component is separately retrieved ~~by a~~, using the filter obstructing the specific frequency band, the peaks of both are respectively ~~peak-held~~, digitally converted, and imported to control means, ~~both~~. Both signals are compared by the control means, and it is determined whether ~~or not~~ knocking is occurring from the compared signals.

Moreover, ~~technology is disclosed in~~ JP-A-61-57830

(pp. 3-4, Figs. 1 and 3) ~~where~~ signals obtained through a filter selectively allowing passing knocking signals ~~to pass~~ ~~from signals~~ based on the ion currents and a filter selectively allowing passing unique vibration frequencies generated by the mechanical dimensions of each cylinder ~~to pass~~ are respectively integrated over a predetermined period, ~~signals detecting~~. Signals indicating the occurrence of knocking are obtained from the ratio of the respective integrated values, ~~and the~~. The signals are integrated during a predetermined number of revolutions, whereby ~~the determination of knocking is conducted~~. detected.

Moreover, ~~technology is disclosed in~~ JP-A-11-295188 (pp. 5-8, Figs. 9 to 11) ~~where~~ signals based on the ion currents are passed through a high-pass filter and a low-pass filter, whereby only a knocking detection-use signal is extracted, ~~the~~. The knocking detection-use signal is A/D converted, ~~thereafter and a~~ discrete Fourier ~~transformed, the frequency is transform is applied~~. The resulting frequencies are analyzed, it is determined from the result of the analysis to determine whether the signal results from knocking or from noise, and the running state of the internal combustion engine is determined.

As described above, these various technologies have been disclosed. However, in the case of Japanese Patent No. 3184451, even if a signal including the knocking component

is detected, it is determined to be invalid if a signal including spark noise is included, and it is mistakenly determined that knocking is not occurring even if knocking is occurring. Also, the ion currents are signals that are small, depending on the running state, and the noise signal becomes large when the operating noise of the injector and external noise, such as from a phone are superposed, so that knocking cannot be completely detected with the methods of JP-A-11-2175 and JP-A-61-57830.

Also, the prior art uses, as the detection target, time intervals ~~where the intervals between each ignition are used as units in relation to knocking detection, and~~. Use of these time intervals cannot accurately detect knocking, ~~which is a phenomenon that because knocking~~ appears and disappears in units of time shorter than these time intervals. For this reason, there has been the problem that control methods cannot be made to correspond to the timing of knocking occurrence. Moreover, there have been ~~the problems that the~~. The resistance of the determination function ~~has been low,~~ with respect to ion current signals whose amplitude has been increased due to the influence of additives added to the fuel ~~and the,~~ is low. The ion currents ~~on which are~~have superposed impulse noise including many frequency components. Also, in all of the prior examples, knocking determination precision has

been low because the time resolution has been low.

#### SUMMARY OF THE INVENTION

The present invention has been made in order to solve these problems, and it is an object thereof to detect, with high precision, the occurrence of knocking and the timing thereof with time units narrower than intervals between ignitions, even in a case where the ion currents generated inside the cylinders of an internal combustion engine are measured and noise is superposed on the ion currents.

A knocking detection apparatus pertaining to the invention comprises: spark plugs disposed in cylinders of an internal combustion engine; ion current detecting means for detecting ion currents flowing in the spark plugs; time-frequency transforming means for setting time intervals ~~allowing, with~~ one or more time overlaps, within a time from ~~after-ignition by the a spark plugs to until~~ its own plug in a corresponding cylinder or in another cylinder, until the next ignitesignition, and sampling current values of the ion currents in the respective time intervals to determine the ~~time-frequency~~ components thereof; knocking detecting means for detecting knocking on the basis of the ~~time-frequency~~ components; and detection control means ~~for inputting a~~ receiving running status of the internal combustion engine and controlling the time-

frequency transforming means and the knocking detecting means.

A knocking detection method pertaining to the invention includes: ion current detecting means for detecting ion currents using spark plugs disposed in cylinders of an internal combustion engine; time-frequency transforming means for setting time intervals allowing ~~one~~ or more time overlaps within a time from after ignition by ~~the~~ a spark plugs to until its own in a corresponding cylinder or another cylinder, until the next ~~ignites~~ ignition, and sampling current values of the ion currents in the respective time intervals to determine the ~~time~~ frequency components thereof; knocking detecting means for detecting knocking on the basis of the ~~time~~ frequency components; and detection control means for controlling the time-frequency transforming means and the knocking detecting means, wherein the ~~detection of knocking is~~ conducted by the detecting control means ~~inputting~~ areceives running status of the internal combustion engine and ~~controlling~~ controls the time-frequency transforming means and the knocking detecting means ~~to determine time~~ determining frequency components from sampled values of the ion currents.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram showing ~~the~~a schematic configuration of a knocking detection apparatus and detection method according to a first embodiment of the invention;

Fig. 2 is a block diagram describing ion current sampling in the knocking detection apparatus and detection method according to the first embodiment of the invention;

Fig. 3 is an explanatory graph of ion current detection intervals in the knocking detection apparatus and detection method according to the first embodiment of the invention;

Figs. ~~4A, 4B~~4(A), 4(B), and 4(C) are explanatory graphs of time-frequency transformation and knocking determination function values in the knocking detection apparatus and detection method according to the first embodiment of the invention; and

Figs. ~~5A, 5B~~5(A), 5(B), and 5(C) are explanatory graphs of time-frequency transformation and knocking determination function values in a knocking detection apparatus and detection method according to a second embodiment of the invention.

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

##### First Embodiment

Figs. 1 to 4(C) are diagrams describing a knocking

detection apparatus and detection method according to a first embodiment of the invention. Fig. 1 is a block diagram showing ~~the~~ a schematic configuration of the knocking detection apparatus and detection method, Fig. 2 is a block diagram describing ion current sampling, Fig. 3 is an explanatory graph showing sampled intervals in ion current detection, and Figs. ~~4A, 4B~~ 4(A), 4(B) and 4(C) are explanatory graphs describing the result of time-frequency transformation of ion currents and knocking determination function values.

In Fig. 1, an ignition device 1 includes a publicly-known ignition circuit, ~~and~~. An ion current detecting means 2 detects an ion current from the current of a secondary ignition circuit and is a publicly-known ion current detection circuit. As described later, time-frequency transforming means 3 ~~conducts~~ applies a Fourier transform so that knocking can be determined from an ion current signal, and knocking detecting means 4 determines the presence of knocking from the result of transformation by the time-frequency transforming means 3 and detects the timing of the knocking.

Detection control means 5 ~~inputs~~ receives the running status of an internal combustion engine, controls the time-frequency transforming means 3 and the knocking detecting means 4, and transforms, in accordance with the running



status of the internal combustion engine, ~~one or both of~~ sampled times of ion current values resulting from the time-frequency transforming means 3 and an ion current sample number serving as the target of time-frequency transformation. The result of detection by the knocking detecting means 4 is given to ignition control means 6, and the ignition control means 6 ~~conducts control of controls~~ ignition times in accordance with the state of knocking.

The time-frequency transforming means 3 includes ion current sampling means 7 and ion current sampled value transforming means 8 shown in Fig. 2. The time-frequency transforming means 3 first determines ion current sampled values  $x(0)$ ,  $x(\Delta t)$ ,  $x(2\Delta t)$ , ... from the detected ion currents with respect to 0,  $\Delta t$ ,  $2\Delta t$ , ... that are ~~times of~~ set fixed intervals from a starting point determined by the detection control means 5. In this embodiment, a case where  $\Delta t = 5\mu s$  is used as an example, but  $\Delta t$  can be optionally set depending on ~~the~~ conditions.

Next, the time-frequency transforming means 3 determines the ~~time~~-frequency components  $C_n(f)$  in ~~the respective~~ time intervals from the ~~ion current~~-sampled ~~values~~ ion currents included in the time intervals represented by the set  $I_n = (T_n, T_n + \Delta T, \dots, T_n + (M-1)\Delta T)$  ~~that are~~. The set allowing overlap of time intervals includes overlaps in an amount determined by the detection

control means 5. That is, here, the time-frequency transforming means 3 sets, as shown in Fig. 3, a set of time intervals allowing with one or more overlaps in the of adjacent time intervals, in the time period from the ignition determined by the detection control means 5 to ~~when its own~~ until ignition occurs in a cylinder or another cylinder ignites, samples the ~~current values of the ion~~ currents with respect to each time interval, and determines the ~~time-frequency components thereof of each ion current sample.~~ In the present embodiment, an example is described wherein which the total number of intervals in the set, M = 256, and time intervals are recursively defined as  $T_{n+1} = T_n + (M/K)\Delta T$  (where  $K = 8$  and  $n = 0, 1, 2, \dots$ ), but the effectiveness of ~~this embodiment~~ the invention is not limited to these values.

~~The~~ A specific way of determining the time-frequency components uses a ~~short-time~~ fast Fourier transform (FFT) using a Hanning window  $W(m)$  of an order  $M$ , defined by the following equation, as one example in this embodiment, but the effectiveness of the invention is not limited to this selection of the Hanning window function.

[Equation 1]

$$W(m) = \{1 - \cos[2\pi(m+1)/(M+1)]\}/2 \quad \dots (1)$$

Here,  $m = (0, 1, 2 \dots M-1)$ , and ~~with respect to the real number x,~~ the symbol  $\cos(x)$  represents a cosine

function of  $x_l$  and the symbol  $\pi$  represents pi.

With respect to the ~~set~~fixed time intervals  $T_n$ , the ~~time~~-frequency components  $C_n(f)$  (where  $f = 0, 1, 2 \dots M-1$ ) ~~is~~are determined by the following equation.

[Equation 2]

$$C_n(f) = \sum_{\{0 \leq m \leq M-1\}} \{x(T_n + m\Delta T) w(m) \exp(-2\pi i f m / (M-1))\} \dots (2)$$

Here, the symbol  $i$  represents ~~an~~the imaginary unit, and ~~with respect to the complex number  $x$~~ ,  $\exp(x)$  represents an exponential function ~~of  $x$~~ . Also, with respect to ~~the~~a sequence in the form  $\{a(m)\}$ , the symbol  $\sum_{\{0 \leq m \leq M-1\}} \{a(m)\}$  represents an operation that corresponds to the sum  $a(0) + a(1) + \dots + a(M-1)$  of the sequence.

Below, with respect to ~~the~~a logical expression  $f(x)$  and the sequence  $a(x)$ ,  $\sum_{\{f(x)\}} \{a(x)\}$  ~~will~~represents an operation that corresponds to the sum  $a(x_0) + a(x_1) + \dots + a(x_k)$  (where  $\{x_0, x_1, x_k\}$  is a set of numbers satisfying the logical expression  $f(x)$ ) of the sequence ~~on~~of the set of  $x_l$  where the logical expression  $f(x)$  becomes ~~the~~a true value.

The knocking detecting means 4 does not require all ~~time~~-frequency components. Because of the condition that the original ion current sampled values are real numbers, all of the ~~time~~-frequency components  $C_n(f)$  (where  $\{f = 0, 1, \dots M-1\}$ ) are not independent of each other. In the time-

frequency transforming means 3, the ~~time~~-frequency components  $C_n(f)$  are determined only with respect to the ~~value~~values of  $f$  necessary to the knocking detecting means 4-~~that~~, which the detection control means 5 determines.

It is commonly known that knocking causes vibrations having as primary components frequencies determined by the shape, pressure, temperature, and molecular weight of a gaseous mixture inside the cylinders. Of those frequencies, the frequency where the amplitude experimentally reaches a maximum is taken as a primary frequency  $f_0$ , and ~~the~~ frequencies at ~~both~~opposite sides ~~thereof~~of the frequency  $f_0$ , where the amplitudes experimentally reach a minimum, are taken as  $f^-$  and  $f^+$ . In this embodiment, only the ~~time~~-frequency components  $C_n(f_0)$ ,  $C_n(f^-)$ , and  $C_n(f^+)$ , with respect to  $f_0 = 6$ ,  $f^- = 3$ , and  $f^+ = 9$ , are calculated, but it is also possible to vary this selection in accordance with ~~the~~running status of the engine. Also, the effectiveness of the invention is not limited to these values.

When knocking occurs and vibrations are caused, the absolute value  $|C_n(f_0)|$  of the primary vibration component ~~takes~~has a large value. ~~Below, the~~(The symbol  $|x|$  ~~will~~represents the absolute value of  $x$ .) However, ~~it~~the primary vibration component can also ~~take~~have a large value when impulse noise is superposed on the ion current.

Thus, in the knocking detecting means 4, the following determination equation is calculated.

[Equation 3]

$$D(n) = (2 \times |C_n(f_0)| - |C_n(f^-)| - |C_n(f^+)|) \quad \dots (3)$$

While ~~this value~~ D(n) takes a large positive value with respect to the ~~ion current sampled values~~ ion currents when vibration caused by knocking arises, it becomes possible to suppress the influence ~~thereof when the ion current values are configured from~~ of impulse noise.

However, when the ion currents themselves are amplified by additives, ~~this~~ the value produced by the determination equation (3) is proportional to the ion current intensity coefficient ~~that,~~ which is the amplification degree ~~thereof.~~ In order to prevent an erroneous determination resulting from this influence, the determination equation is divided by a ~~standard~~ standardizing factor C defined by the following equation.

[Equation 4]

$$EC_n = [\sum \{0 \leq f \leq M/2-1\} \{|C_n(f)|^2\}]^{(1/2)} \quad \dots (4)$$

~~Here, with respect to the complex numbers x, y, the symbol x<sup>y</sup> represents the function of x to the power of y.~~

In this manner, a determination function E(n) ~~whose~~ having high resistance ~~is high with respect to the~~ superposition of impulse noise and changes in the ion current intensity coefficient is obtained ~~by~~ from the

following equation.

[Equation 5]

$$E(n) = (2 \times |C_n(f_0)| - |C_n(f^-)| - |C_n(f^+)|) / [\sum_{0 \leq f \leq M/2-1} \{|C_n(f)|^2\}]^{(1/2)} \quad \dots (5)$$

In the present embodiment, the ~~above~~-determination function value is compared to a preset threshold  $Th$ , but the determination function may be determined by a similar function meeting the above-described ~~resolution~~  
principle-impulse noise resistance.

Figs. ~~4A, 4B~~4(A), 4(B), and 4(C) show results ~~where~~  
~~it is applied to specific data in of this embodiment.~~ The determination function values shown in Fig. 4(C) are obtained from the ion current shown in Fig. 4(A), and knocking can be reliably determined by making the threshold  $Th$  0.1. The change in the intensity of the ~~time~~-frequency components catches the vibration generated by knocking, the values of the determination function greatly exceed the threshold, and knocking is clearly detected. It should be noted that, although ~~a case is in the described as an~~  
~~example where~~  $Th = 0.1$ , in this embodiment, the effectiveness of the invention is not limited to this value.

Second Embodiment

Figs. ~~5A, 5B~~5(A), 5(B), and 5(C) are explanatory graphs describing ion current time-frequency transformation results and knocking determination function values in a

knocking detection apparatus and detection method according to a second embodiment of the invention. In the first embodiment, the ~~time~~-frequency components were determined by a ~~short-time~~fast Fourier transform using a Hanning window function, but in the present embodiment, the window function of equation 6 is used to obtain a Gabor wavelet component.

[Equation 6]

$$w(m) = \exp(-L(m - (M-1)/2)^2) \quad \dots (6)$$

Figs. ~~5A, 5B~~5(A), 5(B), and 5(C) show the results when equation 6 is applied to specific data ~~in~~for this embodiment, and show that the ~~state of the~~ occurrence of knocking greatly exceeds the threshold  $Th = 0.1$  and can be determined. Thus, even in this embodiment, knocking is clearly detected ~~similar to,~~ as in the first embodiment. It should be noted that, although  $L = 800/(M-1)^2$  was used as an example for  $L$  in ~~the above~~ equation 6 ~~in~~for this embodiment, the effectiveness of the invention is not limited to this value.

As described above, the knocking detection apparatus of the invention comprises: spark plugs disposed in cylinders of an internal combustion engine; ion current detecting means for detecting ion currents flowing in the spark plugs; time-frequency transforming means ~~for~~ setting time intervals ~~allowing one or more~~ with overlaps, within a

time from after ignition by ~~the~~ a spark plug ~~to~~ plug in a corresponding cylinder or in another cylinder, until ~~its own cylinder or another cylinder~~ the next ignites ignition, and sampling current values of the ion currents in the respective time intervals to determine the ~~time~~-frequency components thereof; knocking detecting means for detecting knocking on the basis of the ~~time~~-frequency components; and detection control means for ~~inputting a~~ receiving running status of the engine and controlling the time-frequency transforming means and the knocking detecting means. Thus, the knocking detection apparatus of the invention can precisely grasp the distribution of constantly changing combustion energy and can determine knocking and precisely detect the time of occurrence ~~timing thereof~~ of knocking.

The knocking detection method of the invention includes: ion current detecting means for detecting ion currents using spark plugs disposed in cylinders of an internal combustion engine; time-frequency transforming means for setting time intervals ~~allowing one or more~~ with overlaps within a time from ~~after ignition by the~~ of a spark ~~plug~~ to plug in a corresponding cylinder or in another cylinder, until ~~its own cylinder or another cylinder~~ the next ignites ignition, and sampling current values of the ion currents in the respective time intervals to determine the ~~time~~-frequency components thereof; knocking detecting



means for detecting knocking on the basis of the ~~time-~~ frequency components; and detection control means for controlling the time-frequency transforming means and the knocking detecting means, ~~wherein the detection of knocking is conducted including detecting knocking~~ by the detecting control means ~~inputting~~ receiving running status of the internal combustion engine and controlling the time-frequency transforming means and the knocking detecting means to determine ~~time-~~ frequency components from sampled values of the ion currents. Thus, the knocking detection method of the invention can detect knocking without mistaken operation with respect to noise ~~belonging to~~ from different time intervals, can detect knocking without mistaken operation with respect to fuel where the ion current intensity coefficients are different, and enables control of an internal combustion engine in accordance with the occurrence and timing of knocking.